Chapter 14
Effects of Irradiation on Food Bioactives

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14.1 Introduction

Food irradiation is a promising technology that uses ionizing radiation for food processing. Although the history of using food irradiation for several benefits has more than 100 years, only after the 1960's the concept of commercial radiation sources became available. Irradiation is a non-thermal, clean and eco-friendly process, not involving the use of chemicals or generating chemical residues. It has been considered a safe and effective technology by the World Health Organization (WHO), the Food and Agriculture Organization (FAO) and the International Atomic

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Energy Agency (IAEA). Furthermore, it is firmly established that the food does not become radioactive, can be treated in its final packaging, which avoids re-contamination of the products and makes it available for immediate distribution to food suppliers.

In this chapter, after presenting general aspects about irradiation processes, we will discuss the effects of this technology on the food bioactives, as well as the potential applications of these recovered compounds in food, cosmetic and pharmaceutical industries thus promoting the circular economy for sustainable development.

14.2 Irradiation Processes

The three forms of ionizing radiation authorized to be used in food irradiation applications are gamma rays, X-rays and electron-beam accelerators (WHO 1988).

14.2.1 Gamma Radiation

Gamma radiation is generated by photons emitted from the radioactive isotopes cobalt-60 and cesium-137, with energies of 1.17 and 1.33 MeV (^{60}Co) and 0.66 MeV (^{137}Cs).

Cobalt-60 is the most common source of gamma radiation used for food processing. There are more than 200 large-scale gamma plants operating worldwide and this number is growing. The main advantage of these radioisotopes is the high efficiency due to their penetrating power. Nevertheless, when not being used, the gamma sources have to be stored in a water pool in order to absorb the energy and protect workers. In a gamma facility, the food product can be treated in the same boxes or pallets in which they will be transported and distributed, being thus carried into the irradiator, submitted to the radiation source and taken back out again. The isotope source is constituted most often by multiple pencils in known positions (Fig. 14.1). Gamma irradiators are designed to provide an acceptable distribution of absorbed dose within the product through an arrangement of, or pathway for, products in irradiation containers around the radiation source (Fig. 14.1), which allows the products to absorb the radiation from multiple angles (Ferreira et al. 2018).

14.2.2 Electron-Beam Radiation

Electron-beam radiation is produced from electron accelerators (Fig. 14.2) and it can be used directly or, indirectly, converted to X-rays. The beam energy of e-beam accelerators is usually from 80 keV to 10 MeV.

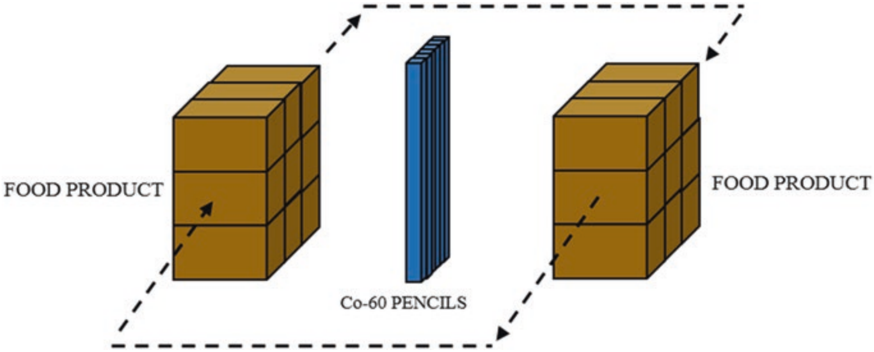

Fig. 14.1 Schematic diagram of a gamma irradiator facility

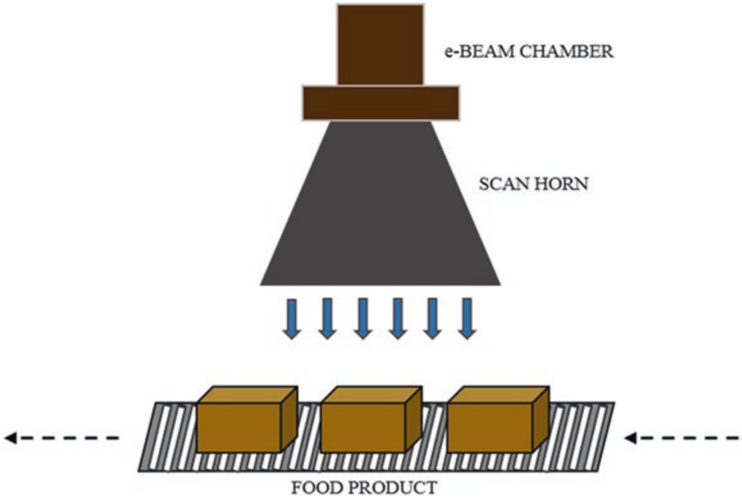

Fig. 14.2 Schematic diagram of an e-beam irradiator

The advantage of electron-beam irradiation is that the source equipment can be switched on and off depending on the necessity and do not rely on a radioactive source that radiates nonstop thus needing to be replaced after some time. In this way, the electron-beam irradiation is a more controlled and energy efficient process and it can also be considered a more environmentally acceptable alternative to ^{60}Co (Ferreira et al. 2018), yet with the disadvantages of a greater complexity of maintenance, lower dose uniformity and lower penetration in the products.

In an accelerator facility, there is a material handling system, the conveyor, that transports the food products to and from the irradiation zone in a precisely and controlled manner (Fig. 14.2) and, in some cases, moves them into and out of the facility (Miller 2005).

14.2.3 X-Rays

X-rays are generated by the same technology that produces electron-beams at or below an energy of 5 MeV, by a process known as Bremsstrahlung conversion (Miller 2005) which happens when electrons are accelerated to a metallic target (e.g. tantalum, tungsten or gold) to be converted to an X-ray steam. Nevertheless, most of the energy required to produce X-rays is lost as heat in the target, turning this process more inefficient and expensive than gamma or electron-beam radiation. Therefore, its throughput efficiency is quite low when compared to that obtained by e-beam. The photons in X-rays are similar to gamma radiation, meaning that they have very high penetration, but without using isotopes as source.

14.3 Dose Range and Dosimetry

Irradiation processing has been studied extensively worldwide and has become accepted as a proven and effective post-harvest treatment to reduce pathogenic contamination, prevent sprouting, eliminate parasites, extend the shelf-life of fresh perishable foods, and provide ready-to-eat food for astronauts and emergency rations and diets for immune-compromised patients, among other applications.

The different purposes on the use of irradiation technology depend on the absorbed radiation dose (Table 14.1), which is the accumulated energy that is transferred to the matter, i.e., absorbed energy per mass unit. The SI unit for dose is the "Gray" (Gy), defined as the absorption of one joule in a mass of 1 kg ($1\ Gy = 1\ J\ kg^{-1}$) of irradiated matter.

Dosimetry provides essential important information in radiation processing. When the food product is exposed to radiation, the absorbed doses and dose rates must be measured prior to its irradiation to determine the performance of the irradiation facility. The dosimetry system consists of the dosimeters, the measurement instruments and their associated reference standards and procedures for correct use. These systems are recommended to characterize the radiation facility for operational qualification, perform dose mappings, quality control and validation of the processes. In this way, the dosimetry systems must be calibrated to ensure that the irradiator is capable of operating and delivering the adequate doses to the product (ISO/ASTM 52303:2015). The minimum (D_{min}) and the maximum (D_{max}) absorbed doses that are applied to a food product in order to achieve the final purpose, maintaining its quality control and assurance, are based on the routine dose monitoring and regulatory limits that may be applicable. The ratio of the maximum dose received by a product stack to the minimum dose received is commonly referred to as the "Dose Uniformity Ratio" (DUR), with DUR = 1.0 as the ideal value. DUR must be optimized by changing, for example, the position of the product in relation to the source or the irradiator design. In food products with high density, the ideal DUR is difficult to achieve.

Table 14.1 Applications of food irradiation and recommended dose ranges

Purpose	Dose range (kGy)	Examples of food treated
Low doses (0.1–1 kGy)		
• Inhibition of sprouting	0.05–0.15	Potatoes, onions, garlic, ginger-root, chestnuts
• Insect disinfestation and parasite disinfection	0.15–0.50	Cereals and pulses, fresh and dried fruits, dried fish and meat, fresh pork
• Delay of physiological process (e.g., ripening)	0.50–1.0	Fresh fruits and vegetables
Medium dose (1–10 kGy)		
• Extension of shelf-life	1.0–3.0	Fresh fish, strawberries, asparagus
• Inhibition of spoilage and pathogenic microorganisms	1.0–7.0	Fresh and frozen seafood, raw or frozen poultry and meat
• Improving technological properties	2.0–7.0	Grapes (increasing juice yield), dehydrated vegetables (reduced cooking time)
High dose (10–50 kGy)		
• Industrial sterilization (in combination with mild heat)	30–50	Meat, poultry, seafood, prepared foods, sterilized hospital diets
• Decontamination of certain food additives and ingredients	10–50	Spices, enzyme preparations, natural gum

Various dosimeters can be used for food processing with a reproducible response to radiation, such as polymethyl methacrylate (PMMA) dosimeters, radiochromic dosimeters and alanine dosimeters. PMMA dosimeters can be measured in a calibrated spectrophotometer at a given specific wavelength to determine the response, the specific absorbance after irradiation and the dosimeter thickness. Alanine dosimeters can be produced in pellets or films and the concentration of free radicals formed during irradiation can be measured by Electron Spin Resonance (ESR). The American Society for Testing and Materials (ASTM) E61 'Radiation Processing' is an international group of experts who have established and maintained standard practices, methods and guides for ionizing radiation processing and dosimetry.

14.4 International Standards on Food Processing

The *Codex Alimentarius*, also known as "food code", is a compilation of all the standards, codes of practice, guidelines and recommendations of the *Codex Alimentarius* Commission, with the objective of protecting consumers' health and ensuring fair practices in the food trade. The proposed guidelines for irradiation are based on findings of the Joint Expert Committee on Food Irradiation (JECFI) composed by experts of the Food and Agriculture Organization, International Atomic Energy Agency and World Health Organization (FAO/IAEA/WHO). In 1981, WHO published a document stating that irradiation of food at doses up to 10.0 kGy is safe and introduces no further toxicological or nutritional problem (JECFI 1981). In 1997, the FAO/IAEA/WHO Study Group on High-Dose Irradiation (JSGHDI 1999) concluded that food irradiated to any dose appropriate to achieve the intended technological objective is both safe to consume and nutritionally adequate and that no upper dose limit has to be imposed.

Food that has been irradiated must be labeled as "irradiated" or "treated with ionizing radiation" together with the Radura symbol (Fig. 14.3) and the name of the product. The word "radura" derived from radurization, a term composed of the initial letters of the word "radiation" and the terms "durus" (Latin word for "hard" or "lasting") (Maherani et al. 2016). Generally, the symbol is green and resembles a plant in a circle that illustrates the rays from the sources (Fig. 14.3).

Currently, food irradiation is approved for using in more than 50 countries worldwide for over 60 products, including Australia, Belgium, Brazil, Canada, China, India, Russia, South Africa, Thailand, USA and Vietnam. In 2015, more than 700,000 tons of foods were irradiated (Eustice 2018), including spices, meat, fresh fruits and vegetables. Based on the *Codex* standards for the Labeling of Prepackaged Foods (CAC 1985), many countries have developed their own national regulations for irradiated food labeling and in most countries there is still no requirement to use the Radura symbol. Furthermore, the list of products allowed to be irradiated differs from country to country. For instance, in the European Union, the Directive 1999/3/EC only permits the irradiation of dried aromatic herbs, spices and vegetable seasonings (European Union 1999).

Fig. 14.3 The Radura symbol

14.5 Consumers' Acceptance

Perhaps consumers' acceptance is the most difficult barrier to cross on the use of irradiation, making their perception an interesting and important point to take into consideration. Although consumers are always interested in new technologies, the truth is that they confuse irradiated food with radioactive food that can cause damage to human health or environment (Ornellas et al. 2006; Junqueira-Gonçalves et al. 2011; Roberts 2014). Actually, the main worries of the consumers include safety, nutrition, detection and labeling of irradiated food. Even so, the public would consider consuming irradiated food if their benefits are explained or if they are informed about the use of "Radura" symbol, which is believed to transmit confidence and safety. In this way, an effort on the education of consumers has to be done, providing scientific and credible information in order to familiarize them with the principles, aims and benefits of irradiated products, which may lead to change their opinion (Maherani et al. 2016).

14.6 Effects of Irradiation on Food Bioactives

Bioactive compounds are phytochemicals naturally found in fruits, vegetables or whole grains that may provide beneficial health effects, including antioxidant, anti-inflammatory, antimicrobial, anticancer and immunomodulatory activities (Kris-Etherton et al. 2002; Shashirekha et al. 2015). They include different classes of compounds, such as polyphenols, carotenoids, tocopherols, phytosterols, organosulfur compounds, fatty acids, betalains, essential oils (terpenes) and alkaloids. They have different chemical structures and solubility (hydrophilic or lipophilic), distribution in nature, range of concentrations in foods, bioavailability in the human body, sites of action, effectiveness against harmful species, specificity and biological action.

When food is exposed to ionizing radiation, some primary effects are induced in food matrices due to the presence of water molecules, via ionization and excitation, which exponentially increase by the secondary action of the free radicals formed during this process. Due to the high water contents in food, the products that are formed during water radiolysis are considered the main responsible for the potential effects on food composition. These products include several chemical species: hydrated electrons (e^{-}_{aq}), hydroxyl radicals ($HO^{\bullet}$), hydrogen radicals ($H^{\bullet}$), excited water molecules (H_2O^{*}), ionized water molecules (H_2O^{+}), hydrogen peroxide (H_2O_2) and diatomic hydrogen molecules (H_2) (Le Caër 2011). The occurring modifications in atoms and molecules are known as the primary or direct effects of radiation, which result in the formation of new chemical compounds and free radicals, both chemically unstable and reactive. These radical species can interact with themselves and/or continue to react with other food components, that could lead to the formation of new compounds that are not present in non-irradiated food (Ferreira et al.

2018). These new reaction products can also interact with the above-mentioned free radicals, representing the secondary or indirect chemical effects of radiation processing (Ferreira et al. 2018).

The irradiation can alter and/or improve the chemical components on food, enhance the extractability of some molecules and change its bioactivity, and these changes may depend on the irradiation conditions (water content, temperature, pH, dose and dose rate). Furthermore, the effects induced by ionizing radiation on the bioactive compounds are also dependent on the food composition. The observed increase in the extractability of compounds can be explained by changes in cellular structures, namely by the depolymerization and dissolution of the cell wall polysaccharides by irradiation (Harrison and Were 2007; Behgar et al. 2011). Thus, the improvement of total phenolic and/or flavonoid contents on irradiated samples can be related with their release from matrix structures, increasing extractability of certain molecules, but also to the degradation of larger compounds into smaller ones by irradiation. The degradation of ascorbic acid, an important vitamin found in different fruits, usually observed after food irradiation can be easily attributed to the reversible oxidation of ascorbic acid to dehydroascorbic acid that can be further hydrolyzed and oxidized irreversibly to 2,3-diketogulonic acid (Deutsch 2000). Oppositely, the increase in the antioxidant activity sometimes produced after irradiation can be associated to an enhancement in enzymes activity (e.g., phenylalanine ammonia-lyase or peroxidase). For instance, stimulation of phenylalanine ammonia-lyase activity may promote the accumulation of anthocyanins, flavonoids and other phenolic compounds (Given et al. 1988; Oufedjikh et al. 2000). It is also pertinent to mention that the increase or decrease in the extraction yield is strongly dependent on the solvents used for the extraction (Pérez et al. 2007; Khattak et al. 2008).

The effects induced by ionizing radiation on food bioactive compounds have been studied for many years and will be reviewed on this section.

14.6.1 Fruits and Vegetables

Fruits and vegetables are colorful, flavorful and nutritious components rich in bioactive compounds, such as polyphenols, carotenoids, vitamins, phytoestrogens, glucosinolates and anthocyanins. Carotenoids and anthocyanins are also important compounds as they are pigments that impart the color to fruits and vegetables.

Some studies have reported the effects of gamma and electron-beam radiation on the major compounds of berry fruits. Barkaoui et al. (2020) compared the impact of gamma and electron-beam radiation on the antioxidants of strawberries (*Fragaria* × *ananassa*), being both treatments capable of preserving the phenolic content and increasing the antioxidant activity of the fruits at 2 kGy. On the other hand, both treatments induced a significant reduction on the amount of L-ascorbic acid (vitamin C). In fact, it is documented that ascorbic acid of berry fruits is sensitive to irradiation (Hussain et al. 2012; Tezotto-Uliana et al. 2013; Elias et al. 2020) and can be oxidized to dehydroascorbic and, consequently, to 2,3-diketogulonic acid (Deutsch 2000). Maraei and Elsawy (2017) reported an increase of phenolic and anthocyanin contents and antioxidant activity in strawberries irradiated at 600 Gy. Furthermore, gamma irradiation at 0.5 kGy was observed to increase the concentration of anthocyanins (Tezotto-Uliana et al. 2013) and doses up to 2 kGy enhanced the phenolic content and antioxidant activity (Cabo Verde et al. 2013; Guimarães et al. 2013) in raspberries (*Rubus idaeus* L.). Electron-beam radiation at 3 kGy preserved the phenolic content and antioxidant activity of raspberries (Elias et al. 2020), and the total anthocyanin content, the antioxidant activity and ascorbic acid amount in blueberries (*Vaccinium corymbosum*, cvs. Collins, Bluecrop) (Kong et al. 2014).

Different effects of ionizing radiation have been found in tomatoes (*Solanum lycopersicum* var. cerasiforme) depending on the variety and/or the harvest conditions. Guerreiro et al. (2016) reported slight increases on total phenolic content of cherry tomatoes irradiated at 3.2 kGy, while a decrease in the concentration of individual phenolic compounds was observed in round tomato (Schindler et al. 2005), not affecting the anthocyanin content (Singh et al. 2016). A decrease in the levels of lycopene, the most representative carotenoid in tomatoes, was reported with 1.5 kGy electron-beam doses (Madureira et al. 2019), which was associated to the isomerization of lycopene. On the other hand, fluctuations in the content of lycopene were observed by Loro et al. (2018) in tomatoes, with increasing and decreasing values at doses up to 1.5 kGy.

Najafabadi et al. (2017) found that gamma radiation at doses up to 2.5 kGy not only increased the content of the total phenol and anthocyanins, but also improved the amount of vitamin C in jujube (*Ziziphus jujuba* var. vulgaris) fruit, while other water-soluble vitamins, as folic acid, thiamine (B_1) and pyridoxine (B_6), decreased significantly at this absorbed dose. Concerning mangoes (*Mangifera indica* L.), the studies developed by Reyes and Cisneros-Zevallos (2007) suggested that electron-beam radiation at doses up to 3.1 kGy did not affect the total phenolic and total carotenoid contents or the antioxidant capacity even after 18 days of storage, despite the observed increase in the levels of flavonols and phenolic acids and the decrease in ascorbic acid content. Other authors reported an increase in phenolic and carotenoid compounds and a decrease in ascorbic acid concentration in stored mangoes irradiated (1–1.5 kGy) with gamma (El-Samahy et al. 2000) and electron-beam (Moreno et al. 2007) radiation. It was also verified that gamma radiation (1–2 kGy) enhanced the antioxidant properties of peach (*Prunus persica* Bausch, Cv. Elberta), due to the increase in total phenolic content via enhancement of phenylalanine ammonia-lyase (PAL) activity (Hussain et al. 2010), despite a reduction of the ascorbic acid concentration. As for irradiated chestnuts (*Castanea sativa* Mill.), it was reported that electron-beam and gamma radiation could preserve total phenolics but not flavonoid content, and increase the antioxidant potential of the fruit, at 1 and 3 kGy, respectively (Carocho et al. 2012). In another study performed by Carocho et al. (2014), 1 kGy absorbed dose was described as capable of preserving phenolic profile and antioxidant properties of chestnuts, leading to higher values of tocopherols and β-carotene bleaching inhibition.

No antioxidant activity assay exactly reflects the antioxidant capacity of the samples. In fact, it is important to assess the antioxidant potential using methods that take into account different mechanisms of action (Moharram and Youssef 2014; Shahidi and Zhong 2015), including, among others, hydrogen atom transfer (HAT), single electron transfer (SET), reducing power and metal chelation. In a study performed by Kavitha et al. (2015) different tendencies were obtained in the evaluation of antioxidant activity of *Zizyphus mauritiana* Lam. fruit using different methodologies. A significant rise was observed in total flavonoids, 1,1-diphenyl-2-picryl-hydrazil (DPPH) scavenging activity and super oxide anion radical scavenging activity, while reducing power, total phenolic content and antioxidant activity measured by thiobarbituric acid reactive substances (TBARS) assay decreased with increasing irradiation doses (0.25–1.0 kGy).

In dry fruits, it was demonstrated that gamma irradiation at 5 kGy was capable of improving the contents of phenolic (>40%) and flavonoid (>56%) compounds, the DPPH scavenging activity (>18%) and the antibacterial potentials of two genotypes of Egyptian date palm fruits, *Phoenix dactylifera* L. (El-Beltagi et al. 2019). Sun dried apricots (*Prunus armeniaca* L.) also underwent a significant increase of total phenols and flavonoids, β-carotene and antioxidant activity after gamma radiation at a dose of 3 kGy (Hussain et al. 2011, 2013). Those authors also analyzed the effect of gamma radiation on individual phenolic acids and flavonoids, observing significant increases in the concentrations of gallic acid (26%), ellagic acid (24%), quercetin (26%) and apigenin (37%) induced by the treatment (Hussain et al. 2013).

The effect of gamma radiation was also evaluated in fresh green vegetables, such as watercress (*Nasturtium officinale* R. Br.) (Pinela et al. 2016, 2018), fenugreek (*Trigonella foenum–graceum* L.) and spinach (*Spinacia oleracea* L.). Gamma radiation at 5 kGy combined with modified atmosphere packaging (MAP) induced an increase on monounsaturated fatty acids (MUFA), tocopherols and total phenolic acids (Pinela et al. 2016, 2018). An increase in total phenols, flavonoids and carotenoids was observed for fenugreek and spinach at doses above 0.75 kGy, which were responsible for increasing the antioxidant activity (Hussain et al. 2016). In spinach, after 1.5 kGy irradiation dose, total phenols, flavonoids and carotenoids increased 3.7%, 15.1% and 21.7%, respectively. Concerning the irradiated fenugreek samples, increases of 2.1%, 3.3% and 8.4% in the concentrations were observed for phenols, flavonoids and carotenoids, respectively. A decrease in the ascorbic acid content and increase on dehydroascorbic acid was also verified after irradiation of both vegetables. Fan (2005) reported that irradiation up to 2 kGy increased the phenolic content and antioxidant capacity of endive (*Cichorium endiva* L), Romaine and Iceberg lettuce (*Lactuca sativa* L) further stored at 7–8 °C for 8 days. After that time, and comparing with non-irradiated samples, the phenolic content increased by 40%, 60% and 25% for Romaine and Iceberg lettuce and endive leaf tissues, respectively. Concerning the antioxidant activity, the increases were 52%, 88% and 34% for Romaine and Iceberg lettuce and endive leaf tissues, respectively. On the other hand, irradiation of baby carrots induced a reduction in the phenolic content of 20% at 1 kGy gamma radiation dose (Hirashima et al. 2013).

Table 14.2 summarizes the documented effects of irradiation on bioactive compounds in fruits and vegetables.

Table 14.2 Effects of ionizing radiation on bioactive compounds in fruits and vegetables

Fruit/vegetable	Radiation source	Applied doses	Main results	References
Fragaria × *ananassa*	γ-radiation	1, 2 and 3 kGy	Preservation of phenolic content; increase of DDPH scavenging activity at 2 kGy; degradation of L-ascorbic acid	Barkaoui et al. (2020)
	e-beam	1, 2 and 3 kGy	Preservation of phenolic compounds; increase of DPPH scavenging activity at 2 kGy; higher reducing power at 1 and 3 kGy; degradation of L-ascorbic acid	
	γ-radiation	300, 600 and 900 Gy	Increase of phenolic and anthocyanin contents and antioxidant activity at 600 Gy and during storage; degradation of ascorbic acid	Maraei and Elsawy (2017)
Rubus idaeus L.	γ-radiation	0.5, 1.0 and 2.0 kGy	Decrease of ascorbic acid levels; increase of anthocyanin content at 0.5 kGy	Tezotto-Uliana et al. (2013)
		0.5, 1.0 and 1.5 kGy	Higher values of phenolics and antioxidant activity at 1.5 kGy	Cabo Verde et al. (2013)
		0.5, 1.0, and 2.0 kGy	Increase of phenolic content and antioxidant activity at 2 kGy after 12 days of cold storage; variable tendency of ascorbic acid depending on the absorbed dose	Guimarães et al. (2013)
	e-beam	3 kGy	Preservation of phenolic content and antioxidant activity; loss of ascorbic acid	Elias et al. (2020)
Vaccinium corymbosum, cvs. Collins, Bluecrop	e-beam	0.5, 1, 2 and 3 kGy	Preservation of anthocyanins after treatment and storage; no significant difference on antioxidant activity and ascorbic acid between non-treated and treated samples, although decreasing with storage	Kong et al. (2014)
Solanum lycopersicum var. cerasiforme	γ-radiation	1.3, 3.2 and 5.7 kGy	Slight increase of phenolic content at 3.2 kGy	Guerreiro et al. (2016)
	e-beam	1.5 and 3.1 kGy	Decrease of lycopene content at 1.5 kGy and preservation of DPPH scavenging activity	Madureira et al. (2019)
Lycopersicon esculentum Mill.	γ-radiation	0.5, 0.75, 1.0, 1.5, 2.0, 3.0 and 4.0 kGy	Preservation of anthocyanins content	Singh et al. (2016)

(continued)

Table 14.2 (continued)

Fruit/vegetable	Radiation source	Applied doses	Main results	References
		0.5, 1.0 and 1.5 kGy	Preservation of ascorbic acid up to 1.5 kGy, although degradation with storage; increase of lycopene at 0.5 kGy	Loro et al. (2018)
		2, 4 and 6 kGy	Radiolytic degradation of ferulic acid, *p*-coumaric acid, rutin and naringenin	Schindler et al. (2005)
Ziziphus jujuba var. vulgaris	γ-radiation	0.5, 1.0, 2.5 and 5.0 kGy	Significant increase in total monomeric anthocyanin (~12%) and total phenolic contents (~6%) up to 2.5 kGy; significant decrease in both parameters at 5 kGy; increase of vitamin C content at 2.5 kGy	Najafabadi et al. (2017)
	e-beam	1, 1.5, and 3.1 kGy	Preservation of total phenolic content, carotenoid content and antioxidant capacity even after 18 days of storage; increase in flavonols and phenolic acids; decrease of ascorbic acid content	Reyes and Cisneros-Zevallos (2007)
Mangifera indica L.	e-beam	1.0, 1.5 and 3.0 kGy	Significant increase of phenolic (55%) and carotenoids (91%) concentrations and antioxidant activity (6%) at 1 kGy	Moreno et al. (2007)
	γ-radiation	0.5, 0.75, 1.0 and 1.5 kGy	Increase of phenolic content with increasing absorbed doses and storage time; increase in carotenoid concentrations with storage, in particular, at 1.5 kGy; slight decrease in ascorbic acid concentration with radiation	El-Samahy et al. (2000)
Prunus persica Bausch, Cv. Elberta	γ-radiation	1.0, 1.2, 1.4, 1.6, 1.8 and 2.0 kGy	Increase of phenolic and anthocyanin contents and PAL activity with irradiation dose and storage until 21 days; reduction of ascorbic acid content with doses higher than 1.6 kGy; improvement of DPPH scavenging activity and FRAP with radiation	Hussain et al. (2010)
Castanea sativa Mill.	γ-radiation	0.5, 1 and 3 kGy	Increase of phenolics (53%), DPPH scavenging activity (71%), β-carotene bleaching inhibition (61%) and TBARS inhibition (83%) at 3 kGy; decrease in flavonoids content (65%) at 1 kGy	Carocho et al. (2012)

(continued)

14.6.2 Beverages

Table 14.2 (continued)

Fruit/vegetable	Radiation source	Applied doses	Main results	References
	e-beam	0.5, 1 and 3 kGy	Increase of phenolics (126%), DPPH scavenging activity (37%), reducing power (60%), β-carotene bleaching inhibition (67%) and TBARS inhibition (84%) at 1 kGy; decrease of flavonoids content (87%) at 1 kGy	
	γ-radiation	1 kGy	Increase of tocopherols, namely γ-tocopherol; increase of β-carotene bleaching inhibition	Carocho et al. (2014)
	e-beam	1 kGy	Increase of α- and γ-tocopherols; increase of β-carotene bleaching inhibition	
Zizyphus mauritiana Lam.	γ-radiation	0.25, 0.5, 0.75 and 1 kGy	Increase of total flavonoid and decrease of total phenolic contents at doses up to 1 kGy; increase of DPPH scavenging activity and reduction of reducing power with increasing doses	Kavitha et al. (2015)
Dried *Phoenix dactylifera* L. fruits	γ-radiation	2.5, 5.0 and 10.0 kGy	Improvement of phenolic (>40%), flavonoid (>56%) contents, DPPH scavenging activity (>18%) and antibacterial potential at 5 kGy	El-Beltagi et al. (2019)
Dried *Prunus armeniaca* L. fruits	γ-radiation	1.0, 1.5, 2.0, 2.5 and 3.0 kGy	Linear increase of β-carotene with increasing absorbed doses	Hussain et al. (2011)
		3 kGy	Significant increase of total phenolics (12%), total flavonoids (16%) and β-carotene (37%); increase in DPPH scavenging activity (23%), FRAP (14%) and β-carotene bleaching inhibition (74%); enhancement of gallic acid (26%), ellagic acid (24%), quercetin (26%) and apigenin (37%) concentrations	Hussain et al. (2013)
Nasturtium officinale R. Br.	γ-radiation	1, 2 and 5 kGy	Preservation of antioxidant activity and total flavonoids at 5 kGy; increase of MUFA, tocopherols and total phenolics at 5 kGy	Pinela et al. (2016)
Trigonella foenum–graceum L.	γ-radiation	0.25, 0.5, 0.75, 1.0, 1.25 and 1.5 kGy	Increase of total phenols (2.1%), flavonoids (3.3%) and carotenoids (8.4%) and antioxidant potential at 1.5 kGy; loss of ascorbic acid and increase in dehydroascorbic acid after irradiation	Hussain et al. (2016)

(continued)

Table 14.2 (continued)

Fruit/vegetable	Radiation source	Applied doses	Main results	References
Spinacia oleracea L.			Increase of total phenols (3.7%), flavonoids (15.1%) and carotenoids (21.7%) and antioxidant activity after 1.5 kGy; reduction of ascorbic acid content and increase in dehydroascorbic acid after irradiation	
Cichorium endiva L.	γ-radiation	0.5, 1 and 2 kGy	Increase of phenolic content (25%) and antioxidant capacity (34%) at 2 kGy, after 8 days of storage	Fan (2005)
Romaine *Lactuca sativa* L.			Increase of phenolic content (40%) and antioxidant capacity (52%) at 2 kGy, after 8 days of storage	
Iceberg *Lactuca sativa* L.			Increase of phenolic content (60%) and antioxidant capacity (88%) at 2 kGy, after 8 days of storage	
Baby carrots	γ-radiation	0.5 and 1 kGy	20% reduction of phenolic content at 1 kGy	Hirashima et al. (2013)

Notes: PAL (Phenylalanine ammonia-lyase); DPPH (2,2-Diphenyl-1-picrylhydrazyl); FRAP (Ferric reducing power); TBARS (Thiobarbituric acid reactive substances); MUFA (Monounsaturated fatty acids)

Juices from vegetables (Song et al. 2006; Lee et al. 2009) and fruits (Girennavar et al. 2008; McDonald et al. 2013; Eissa et al. 2014; Shahbaz et al. 2014; Arjeh et al. 2015; Naresh et al. 2015) showed interesting results when subjected to radiation. In carrot (*Daucus carota* var. *sativa*) juices, after storage of 3 days, an increase in the phenolic content (1912.5 μg/mL of sample) and FRAP value (1349.7 mM FRAP/mL of sample) were observed in irradiated samples when compared to the non-irradiated and non-stored sample (1732.9 μg/mL of sample and 931.3 mM FRAP/mL, respectively, for phenolic and FRAP values) (Song et al. 2006). On the contrary, the levels of total phenolics (9121.7 μg/mL of sample) and antioxidant potential value (5776.2 mM FRAP/mL of sample) in irradiated kale (*Brassica oleracea* var. *acephala*) juice were significantly lower than the control (9635.5 μg/mL and 6251.8 mM FRAP/mL, respectively) (Song et al. 2006), and flavonoid content did not change (Jo et al. 2012). In irradiated tamarind (*Tamarindus indica* L.) juice, higher phenolic content and antioxidant activity were found at 5 kGy (Lee et al. 2009).

Low doses (up to 600 Gy) of gamma radiation caused no effect on ascorbic acid, phenolic content and antioxidant activity of orange juice (*Citrus sinensis* L. Osbeck) (McDonald et al. 2013). In watermelon (*Citrullus lanatus* cv.) and mango (*Mangifera indica* L.) juices (fresh and stored) irradiated at 3 and 5 kGy, both total phenolics and flavonoids contents were higher (15-48%) than in non-irradiated samples, although vitamin C and lycopene contents were lower (Eissa et al. 2014; Naresh et al. 2015). An enhancement in the antioxidant activity in both irradiated juices was also observed with increasing irradiation dose. Furthermore, gamma radiation induced increases in the levels of individual phenolic acids present in mango juice, as gallic acid, chlorogenic acid and syringic acid by 3.2, 2.3 and 2.5 fold, respectively (Naresh et al. 2015). Shahbaz et al. (2014) observed a decrease in DPPH and ABTS scavenging activities probably associated with a reduction on anthocyanins and total phenolic contents of irradiated (1–2 kGy) pomegranate (*Punica granatum* L.) juice. The same observations were made by Arjeh et al. (2015) for sour cherry (*Prunus cerasus* L.) juice, with reductions in monomeric anthocyanins of more than 60% at 3 kGy after 60 days. In a study performed on grapefruit (*Citrus paradisi* Macf.) irradiated at doses ranging from 1 to 10 kGy and further juiced, electron-beam radiation was found to significantly reduce the vitamin C and lycopene contents, as well as those of nomilin (a terpenoid limonoid) and dihydroxybergamottin (a furanomcoumarin); on the other hand, naringin level was significantly higher in irradiated juice in comparison with the control sample (Girennavar et al. 2008).

Teas are the most widely consumed beverages in the world. In black tea, made from leaves of *Camellia sinensis* (L.) O. Kuntze, gamma radiation up to 2 kGy increased the total phenolic content, with lower water activity having positive influence on the obtained results (Fanaro et al. 2014). Gerolis et al. (2017) studied the effect of gamma radiation on total antioxidant capacity of green tea (*Camellia sinensis* (L.) O. Kuntze), yerba mate (*Ilex paraguariensis* A. St. Hil.) and chamomile tea (*Matricaria recutita* L.), reporting that this technology can reduce the capacity of some antioxidants and improve the capacity of others, which depends on the compounds present, solvents used and also the method of assessment. In another study developed by Janiak et al. (2017), different Bulgarian teas were studied: Mursalski tea (*Sideritis scardica* Gris), Mashterka tea (*Thymus serpyllum* L.), Good Night tea (tea mix), Staroplaninski tea (Balkan tea mix), Trakia tea (tea mix), and Mountain tea (Planinski tea mix). The authors observed improvement in tannin and phenolic contents and antioxidant capacity in some teas but not in others. Tables 14.3 and 14.4 outline the reported effects of ionizing radiation on the bioactivity of beverages.

14.6.3 Meat

Meat is widely consumed as a main source of proteins, vitamins, minerals and fatty acids. Losses of α-tocopherol and thiamine and riboflavin were observed in irradiated beef, lamb, pork and turkey with doses up to 9 kGy (Fox et al. 1995; Lakritz et al. 1995). On the other hand, significant higher levels of riboflavin and niacin were detected in pork chops and chicken breasts irradiated at the dose range 2–4 kGy (Fox et al. 1989). Fatty acids present in beef and ground beef were also significantly increased at doses up to 7 kGy (Yilmaz and Geçgel 2007; Haque et al. 2017). On Table 14.5 the reported effects of irradiation on the bioactives content of meat are collected.

Table 14.3 Effects of ionizing radiation on the bioactivity of beverages

Fruit/ vegetable beverage	Radiation source	Applied doses	Main results	References
Daucus carota var. *sativa* juice	γ-radiation	3 and 5 kGy	Significant increase of phenolic content and FRAP value in irradiated samples, even after 3 days of storage	Song et al. (2006)
Brassica oleracea var. *acephala* juice			Lower phenolic content and FRAP value in irradiated samples	
		1, 3, and 5 kGy	Slight increase of phenolic content with irradiation; no variation of flavonoid content; reduction of ascorbic acid content with irradiation	Jo et al. (2012)
Angelica keiskei Ito juice	γ-radiation	1, 3, and 5 kGy	Slight increase of phenolic content with irradiation; no variation of flavonoid content; reduction of ascorbic acid content with irradiation	Jo et al. (2012)
Tamarindus indica L. juice	γ-radiation	1, 3, and 5 kGy	Higher total phenolic content and antioxidant activity by DPPH and FRAP at 3 and 5 kGy	Lee et al. (2009)
Citrus sinensis L. Osbeck juice	γ-radiation	200, 400 and 600 Gy	No effect on ascorbic acid, phenolic content and antioxidant activity.	McDonald et al. (2013)
Citrullus lanatus cv. juice	γ-radiation	1, 3 and 5 kGy	Increase of phenolics and flavonoids contents with irradiation; reduction of vitamin C at 3 and 5 kGy; lower lycopene content at 1 kGy; enhancement of DPPH scavenging activity	Eissa et al. (2014)
Mangifera indica L. juice	γ-radiation	1, 3 and 5 kGy	Increase of total phenolic content with increasing doses; increase of total flavonoids at 3 and 5 kGy; decrease of ascorbic acid concentration with increasing doses; increase of DPPH scavenging activity with doses; enhancement in the concentrations of individual phenolic at 3 and 5 kGy: gallic acid, protocatechuic acid, syringic acid, chlorogenic acid, and rutin, and ellagic acid and *p*-coumaric acid at 5 kGy	Naresh et al. (2015)
Punica granatum L. juice	γ-radiation	0.4, 1, and 2 kGy	Decrease in total phenolic compounds, DPPH and ABTS scavenging abilities at 1 and 2 kGy	Shahbaz et al. (2014)

(continued)

Table 14.3 (continued)

Fruit/ vegetable beverage	Radiation source	Applied doses	Main results	References
Prunus cerasus L. juice	γ-radiation	0.5, 1.5, 3.0, 4.5, and 6.0 kGy	No significant difference in total phenolic content with irradiation; reduction of monomeric anthocyanins (>60%) at 3 kGy after 60 days; decrease of DPPH scavenging activity at doses >3 kGy (21%) and storage (29%); decrease in FRAP values by 20% after irradiation and 27% after storage	Arjeh et al. (2015)
Citrus paradisi Macf. juice	e-beam	1.0, 2.5, 5.0, and 10.0 kGy	Significant reduction of the vitamin C and lycopene contents at doses >2.5 kGy; preservation of β-carotene; decrease of nomilin and dihydroxybergamottin contents; increase of naringin at doses >2.5 kGy	Girennavar et al. (2008)

Notes: PAL (Phenylalanine ammonia-lyase); DPPH (2,2-Diphenyl-1-picrylhydrazyl); FRAP (Ferric reducing power); TBARS (Thiobarbituric acid reactive substances); MUFA (Monounsaturated fatty acids); ABTS (2,2′-Azinobis-(3-ethylbenzthiazolin-6-sulfonic acid)

14.6.4 Aromatic and Medicinal Plants

The effect of ionizing radiation on the phytochemicals can vary according to the plant material and the applied dose. Pereira and co-workers showed that gamma radiation at 10 kGy increased significantly (>1-fold) the content of polyphenols in ethanolic extracts and infusions of *Mentha* × *piperita* L. (peppermint), *Aloysia citrodora* Paláu (lemon verbena) and *Thymus vulgaris* L. (thyme) in comparison with the control sample (0 kGy) (Pereira et al. 2017, 2018).

In other studies, the same authors observed that an absorbed dose of 10 kGy of gamma radiation could improve the extractability of phenolic compounds (3.5–5.5 fold) and their antioxidant properties in both infusions and methanol/water extracts of *Ginkgo biloba* L. (Pereira et al. 2015a, b). An increase of 35% in total phenolic content was reported in water extracts of *Rosmarinus officinalis* L. irradiated at 30 kGy, but not in methanol or ethanol extracts (Pérez et al. 2007). The authors hypothesized that this increase could be associated with the presence of phenolic diterpenes in rosemary that result in water-soluble quinone-type compounds by gamma radiation. A previous study developed by Horváthová et al. (2007) revealed a slight increase in the total phenolic content of *Origanum vulgare* L. extracts prepared from samples irradiated at 10 kGy. Gamma irradiation of *Petroselinum crispum* (Mill.) Fuss var. neapolitanum induced a reduction in vitamin C content at 2.7 kGy, while increased total polyphenols in doses up to 2.0 kGy (Cătunescu et al. 2017). By contrast, *Salvia officinalis* L. gamma irradiated at 2 and 4 kGy demonstrated lower antioxidant capacity associated to a lower polyphenolic content (30 and 45%, respectively) (Salem et al. 2013).

Table 14.4 Effects of ionizing radiation on teas

Tea	Radiation source	Applied doses	Main results	References
Camellia sinensis L. O. Kuntze	γ-radiation	1.0, 1.5, 2.0, 2.5, 5.0, 7.5 and 10.0 kGy	Increase of total phenolic compounds at 2 kGy (for 0.183 and 0.651 water activity) or at 5 kGy (for 0.924 water activity); preservation of antioxidant activity; increase of caffeine concentration at 10 kGy	Fanaro et al. (2014)
		20 kGy	Decrease of phenolics level; decrease of flavonoids contents in methanolic extracts; no significant difference in ABTS activity between irradiated and non-irradiated samples	Gerolis et al. (2017)
Ilex paraguariensis A. St. Hil.	γ-radiation	20 kGy	Decrease of phenolics content; preservation of flavonoids content; no significant difference in ABTS activity; decrease of DPHH scavenging activity	
Matricaria recutita L.	γ-radiation	20 kGy	Preservation of phenolics content; decrease of flavonoids content in methanolic extracts; increase of β-carotene bleaching inhibition of water infusions with irradiation; decrease of DPPH scavenging activity	
Mursalski tea (*Sideritis scardica* Gris)	γ-radiation	5 kGy	Improvement of FRAP values and ABTS scavenging activity with irradiation	Janiak et al. (2017)
Mashterka tea (*Thymus serpyllum* L.)	γ-radiation		Increase of DPPH scavenging activity in irradiated samples	
Good Night tea	γ-radiation		Preservation of phenolics content and antioxidant activity	
Staroplaninski tea	γ-radiation		Increase of DPPH scavenging activity with irradiation; improvement of FRAP values and ABTS scavenging activity with irradiation	
Trakia tea	γ-radiation		Increase of total phenolics and tannins contents; improvement of FRAP values and ABTS scavenging activity with irradiation	
Mountain tea	γ-radiation		Increase of tannins content; improvement of FRAP values and ABTS scavenging activity with irradiation	

Notes: DPPH (2,2-Diphenyl-1-picrylhydrazyl); FRAP (Ferric reducing power); ABTS (2,2′-Azinobis-(3-Ethylbenzthiazolin-6-sulfonic acid)

Table 14.5 Effects of ionizing radiation on bioactive compounds of meat

Meat	Radiation source	Applied doses	Main results	References
Beef	γ-radiation	2, 4 and 6 kGy	Increase of free fatty acids with irradiation	Haque et al. (2017)
		0.24, 0.47, 0.94, 1.88, 2.81, 5.62 and 9.37 kGy	Loss of α-tocopherol	Lakritz et al. (1995)
			Reduction of thiamine and riboflavin levels with irradiation	Fox et al. (1995)
Ground beef	γ-radiation	1, 3, 5 and 7 kGy	Significant increase of *trans* fatty acids with irradiation	Yilmaz and Geçgel (2007)
Turkey	γ-radiation	0.24, 0.47, 0.94, 1.88, 2.81, 5.62 and 9.37 kGy	Loss of α-tocopherol	Lakritz et al. (1995)
			Reduction of thiamine and riboflavin levels with irradiation	Fox et al. (1995)
Pork	γ-radiation	0.24, 0.47, 0.94, 1.88, 2.81, 5.62 and 9.37 kGy	Loss of α-tocopherol	Lakritz et al. (1995)
			Reduction of thiamine and riboflavin levels with irradiation	Fox et al. (1995)
		0.5, 1.75, 3.50, 5.25 and 7.0 kGy	Loss of thiamine with increasing doses; increase of riboflavin and niacin levels at 4 kGy	Fox et al. (1989)
Lamb	γ-radiation	0.24, 0.47, 0.94, 1.88, 2.81, 5.62 and 9.37 kGy	Loss of α-tocopherol	Lakritz et al. (1995)
Chicken	γ-radiation	0.5, 1.75, 3.50, 5.25 and 7.0 kGy	Loss of thiamine with increasing doses; increase of riboflavin and niacin levels at 4 kGy	Fox et al. (1989)
		0.24, 0.47, 0.94, 1.88, 2.81, 5.62 and 9.37 kGy	Reduction of thiamine and riboflavin levels with irradiation	Fox et al. (1995)

Concerning medicinal plants, Pereira et al. (2014) observed higher contents of phenolics (107.45 mg GAE/g) and flavonoids (and 33.77 mg CE/g) in the methanolic extracts of medicinal plant borututu (*Cochlospermum angolensis* Welw.) irradiated at 10 kGy, which was correlated with an increase in the antioxidant activity. Similarly, the scavenging activity of *Amoora rohitaka* ethanolic extracts improved by 112%, while the phenolic content and reducing power of methanolic extracts was enhanced by more than 30% at 5 kGy (Rajurkar and Gaikwad 2012). A summary of the results regarding bioactive compounds in irradiated aromatic and medicinal plants is collected in Table 14.6.

14.6.5 Legumes, Cereals and Grains

Legumes are an important group of plant foodstuffs, especially in developing countries, being recognized as a cheap source of protein. Zhu et al. (2010) evaluated the effect of gamma radiation (2–10 kGy) on the phenolic compounds of three different genotypes (black, red and white) of *Oryza sativa* L. grains. The authors reported an increase of phenolic acids content in black rice extracts irradiated at 8 kGy (423.3 mg/kg) compared with the control (381.6 mg/kg), although lower doses promoted a decrease on these acids. On the other hand, irradiation at 6 kGy caused a significant increase (378.3 mg/kg) in anthocyanins content, in comparison with the control (346.6 mg/kg). Similarly, distinct effects of irradiation were observed in different genotypes of rice grains depending on the analyzed variable and absorbed doses (Shao et al. 2013).

The extraction of phenolic compounds from *Nigella sativa* L. seeds using different solvents was evaluated by Khattak et al. (2008). The authors reported that a radiation dose up to 16 kGy improved total extraction yields (3.7%, 4.2%, 9.0% and 5.6% for hexane, acetone, methanol and water, respectively), phenolic contents (2.7% in acetone extracts) and DPPH scavenging activity (10.6% and 5.4% in acetone and methanol extracts, respectively). In a study conducted by Bhat et al. (2007), the levels of total phenolics of *Mucuna pruriens* L. seeds were found to be dose-dependent, significantly increasing at doses higher than 2.5 kGy (73.4 g/kg and 116 g/kg for control and 30 kGy, respectively) while doses higher than 7.5 kGy resulted in a tannin concentration increase (2.62 g/kg for control and 5.81 g/kg for 30 kGy). Also, Siddhuraju et al. (2002) found that irradiation (2–6 kGy) after aqueous soaking increased (>1-fold) the phenolics levels in seeds of three different species of *Sesbania* (*Sesbania aculeata*, *S. rostrata* and *S. cannabina*) and one species of *Vigna* (*Vigna radiata*), attributing this increase to a higher extractability by depolymerization and dissolution of cell wall polysaccharides by irradiation.

Concerning the irradiation of soybeans (*Glycine max* (L.) Merr.), an absorbed dose of 1 kGy was enough to increase total phenolics (10%) and tannins (21.6%), which was correlated with an increase in the antioxidant activity (Štajner et al. 2007). Also, the total isoflavone content (genistein, daidzein, genistin and daidzin) increased at an applied dose of 10 kGy (666.1 mg/kg for control sample and 755.2 mg/kg for 10 kGy sample) (Popović et al. 2013). Variyar et al. (2004) observed an increase higher than onefold in aglycon content with the increase in absorbed doses (0.5–5 kGy) and consequent increase in DPPH scavenging activity, associated with the higher levels of isoflavones in treated samples. Gamma radiation at 1 kGy applied in red kidney beans (*Phaseolus vulgaris*), slightly improved phenolic content and antioxidant activity by DPPH free radical scavenging assay and inhibition in lipid peroxidation, keeping constant even after 6 months of storage (Marathe et al. 2016). Table 14.7 summarizes the effects of irradiation on the bioactive compounds in legumes, cereals and other grains.

Table 14.6 Effects of ionizing radiation on bioactive compounds of aromatic and medicinal plants

Aromatic and medicinal plant	Radiation source	Applied doses	Main results	References
Aloysia citrodora L.	γ-radiation	1, 5 and 10 kGy	Increase of verbascoside at 1 kGy	Pereira et al. (2018)
Mentha × piperita L.			Increase of eriodictyol-7-*O*-rutinoside, luteolin-7-*O*- rutinoside and rosmarinic acid concentrations at 5 kGy	
Thymus vulgaris L.			Increase of luteolin-7-*O*-glucuronide, luteolin-*O*-glucuronide and eriodictyol-*O*-glucuronide at 5 kGy; increase of apigenin-6,8-*C*-dihexoside and eriodictyol-7-*O*-glucuronide at 10 kGy	
Ginkgo biloba L.	γ-radiation	1 and 10 kGy	Improvement of the extractability of phenolic acids and flavonoids at 10 kGy in infusions and methanol/water extracts.	Pereira et al. (2015b)
			Increase of α-tocopherol levels at 1 kGy; increase of antioxidant activity with irradiation	Pereira et al. (2015a)
Rosmarinus officinalis L.	γ-radiation	30 kGy	Increase of total phenolic content by 35% in water extracts after treatment; increase of antioxidant activity (DPPH scavenging and reducing power) in ethanol and water extracts	Pérez et al. (2007)
Origanum vulgare L.	γ-radiation	5, 10 and 30 kGy	Significant increase of total phenolic content at 10 kGy; preservation of DPPH scavenging activity	Horváthová et al. (2007)
Salvia officinalis L.	γ-radiation	2 and 4 kGy	Decrease of total phenolics (>30%) and antioxidant activity (>11%) with irradiation	Salem et al. (2013)
Petroselinum crispum (Mill.) Fuss Var. Neapolitanum	γ-radiation	0.7, 1.4, 2.0 and 2.7 kGy	Decrease of ascorbic acid with irradiation; increase of total polyphenols at 0.7 and 2 kGy; decrease in radical scavenging activity at 2.7 kGy	Cătunescu et al. (2017)

(continued)

Table 14.6 (continued)

Aromatic and medicinal plant	Radiation source	Applied doses	Main results	References
Cochlospermum angolensis Welw.	γ-radiation	1 and 10 kGy	Increase of tocopherols at 1 kGy; increase of phenolics and flavonoids at 10 kGy; higher antioxidant activity (DPPH scavenging activity, reducing power, β-carotene bleaching inhibition and TBARS inhibition) in infusions irradiated at 10 kGy; higher antioxidant activity (DPPH scavenging activity, reducing power and TBARS inhibition) in infusions irradiated at 10 kGy	Pereira et al. (2014)
Amoora rohitaka (Rxb.) Wight & Arn	γ-radiation	1, 3 and 5 kGy	Increase of total phenolics with irradiation; increase of ABTS scavenging activity; increase of FRAP values in methanol extracts up to 5 kGy; increase of DPPH scavenging activity in aqueous and ethanol extracts	Rajurkar and Gaikwad (2012)

Notes: DPPH (2,2-Diphenyl-1-picrylhydrazyl); ABTS (2,2′-Azinobis-(3-Ethylbenzthiazolin-6-sulfonic acid)

14.6.6 Spices

Even in small quantities, spices are a potential source of natural contamination by mesophylic, sporogenic, and asporogenic bacteria, hyphomycetes, and faecal coliforms into foodstuffs where they are added (Sádecká 2007). Hence, ionizing radiation treatment is mostly used in order to eliminate the microbial contamination. Furthermore, some studies were also performed reporting the impact of this technology on the antioxidant properties of different spices.

Variyar et al. (1998) studied the effect of gamma radiation (10 kGy) in five commercially important spices: cinnamon (*Cinnamomum verum* J. Presl.), clove (*Zyzygium aromaticum*), cardamom (*Elettaria cardamomum* (L.) Maton), nutmeg and mace (*Myristica fragrans* Houtt.). In clove, the concentrations of gallic acid and syringic acid increased considerably (384.9 ± 11.6 and 33.0 ± 4.7 mg/kg dry weight, respectively) in the 10 kGy sample in comparison with the control sample (174.7 ± 7.29 and 7.9 ± 1.3 mg/kg dry weight, respectively). In irradiated nutmeg, the concentrations of some observed phenolic acids, such as syringic acid, caffeic acid + vanillic acid, gentisic acid + *p*-hydroxybenzoic acid, also increased at 10 kGy irradiation dose (five-fold, three-fold and six-fold, respectively). The increased level of these phenolic acids in clove and nutmeg could be justified by the degradation of hydrolysable tannins and consequent higher extractability of phenolic acids.

The antioxidant properties of irradiated (5–30 kGy) black pepper (*Piper nigrum* L.), clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry) and ginger (*Zingiber*

Table 14.7 Effects of ionizing radiation on bioactive compounds of legumes, cereals and grains

Legume, cereal and grain	Radiation source	Applied doses	Main results	References
Black rice	γ-radiation	2, 4, 6, 8, and 10 kGy	Increase of phenolic acids content at 8 kGy; highest level of anthocyanins at 6 kGy	Zhu et al. (2010)
		2, 4, 6, 8, and 10 kGy	Increase of antioxidant activity with doses 2–8 kGy	Shao et al. (2013)
White rice	γ-radiation	2, 4, 6, 8, and 10 kGy	Decrease of phenolic acids content with irradiation	Zhu et al. (2010)
		2, 4, 6, 8, and 10 kGy	Increase of total phenolics at 10 kGy; significant increase of antioxidant activity at 10 kGy	Shao et al. (2013)
Red rice	γ-radiation	2, 4, 6, 8, and 10 kGy	Decrease of phenolic acids content with irradiation	Zhu et al. (2010)
		2, 4, 6, 8, and 10 kGy	Enhancement of total phenolics at >6 kGy; Significant increase of antioxidant activity at 8 kGy	Shao et al. (2013)
Nigella sativa L.	γ-radiation	2, 4, 8, 10, 12 and 16 kGy	Improvement in the extraction yields (3.7%, 4.2%, 9.0% and 5.6% for hexane, acetone, methanol and water, respectively) at doses up to 16 kGy; increase by 2.7% of phenolic contents at 16 kGy in acetone extracts; enhancement of DPPH scavenging activity by 10.6% in acetone and 5.4% in methanol extracts	Khattak et al. (2008)
Mucuna pruriens L.	γ-radiation	2.5, 5.0, 7.5, 10, 15 and 30 kGy	2-Fold increase of total phenolics for doses >2.5 kGy and tannins concentrations at doses >7.5 kGy	Bhat et al. (2007)
Sesbania aculeate (Willd.) Pers.	γ-radiation	2, 4 and 6 kGy	Increase of total phenolics at 2 kGy; preservation of tannins with irradiation	Siddhuraju et al. (2002)
Sesbania rostrate Bremek. & Oberm			Increase of total phenolics at 2 kGy; preservation of tannins with irradiation	
Sesbania cannabina (Retz.) Pers.			Preservation of total phenolics tannins with irradiation	
Vigna radiate (L.) R.Wilczek			Increase of total phenolics and tannins at 2 kGy; increase of condensed tannins with irradiation	

(continued)

Table 14.7 (continued)

Legume, cereal and grain	Radiation source	Applied doses	Main results	References
Glycine max (L.) Merr.	γ-radiation	1, 2, 4, 6, 8 and 10 kGy	Highest values of phenolic compounds and tannins at 1 kGy; increase (17%) of FRAP value at 1 kGy; increase of DPPH scavenging activity with increasing irradiation doses	Štajner et al. (2007)
		1, 2, 4 and 10 kGy	Significant increase of total isoflavone content at 10 kGy; significant increase of genistein, daidzein, genistin and daidzin concentrations at 4 kGy; significant increase of total phenolic and tannin contents with irradiation; increase of DPPH scavenging activity with irradiation	Popović et al. (2013)
		0.5, 1, and 5 kGy	Decrease of total isoflavones with irradiation; increase (>1-fold) of isoflavone aglycones content with the increasing of absorbed doses; significant increase in DPPH scavenging activity with irradiation	Variyar et al. (2004)
Phaseolus vulgaris L	γ-radiation	0.25, 1.0, 5.0 and 10.0 kGy	Increase of fatty acids at 10 kGy; increase of free phenolic compounds and antioxidant activity at 1 kGy	Marathe et al. (2016)

Notes: DPPH (2,2-Diphenyl-1-picrylhydrazyl); FRAP (Ferric reducing power)

officinale Roscoe) were also evaluated (Suhaj et al. 2006; Suhaj and Horváthová 2007). The results demonstrated that DPPH scavenging activity of black pepper extracts initially decreased with increasing doses, however, after 2 months of storage, a significant increase of those values occurred due to the increase of dry matter content during the storage. On the other hand, a decrease in the reducing power of these samples was observed with increasing dose and during storage (Suhaj et al. 2006). Suhaj and Horváthová (2007) did not detect variations in phenolic compounds, antiradical activity and reducing power of irradiated clove extracts, even after 5 months of storage, except for phenolic compounds, which were observed to decrease. Contrarily, in ginger, all the parameters (phenolics, antiradical activity and reducing power) kept constant immediately after irradiation but significantly increased by 10% with storage, in particular in those irradiated at 10 and 20 kGy. In Table 14.8 the main effects of irradiation on the bioactive compounds of spices are outlined.

14.6.7 Edible Flowers

Edible flowers have been used in many culinary preparations to improve the sensorial and nutritional qualities of food, by adding color, flavor, taste and visual appeal to salads, sauces, garnish, entrees, drinks or desserts. In this way, it is important to improve the conservation and safety of these products.

Viola tricolor L. (heartseases) and *Tropaeolum majus* L. (garden nasturtium) flowers irradiated by gamma and electron beam radiation at 1 kGy demonstrated higher capacity to scavenge DPPH and to inhibit β-carotene bleaching than not irradiated samples, attributed to an increase in the levels of phenolic compounds, despite the content of anthocyanins decreased (Koike et al. 2015a, b). In addition, the authors reported no significant differences in the observed effects between gamma and electron-beam irradiation, concluding that both technologies can be used to preserve the edible flowers quality (Table 14.9).

Table 14.8 Effects of ionizing radiation on bioactive compounds of spices

Spice	Radiation source	Applied doses	Main results	References
Cinnamomum verum J.Presl	γ-radiation	10 kGy	Increase of protocatechuic acid concentration	Variyar et al. (1998)
Zyzygium aromaticum			Significant increase of gallic acid and syringic acid concentrations; decrease of *p*-coumaric acid and ferulic acid + sinapic acid concentrations	
Elettaria cardamomum (L.) Maton			Preservation of phenolic acids contents	
Myristica fragrans Houtt.			Preservation of phenolic acids concentrations	
Nutmeg			Significant increase of gentisic acid + *p*-hydroxybenzoic acid, caffeic acid + vanillic acid and syringic acid concentrations	
Piper nigrum L.	γ-radiation	5, 7.5, 10, 20, and 30 kGy	Significant decrease of DPPH scavenging activity; decrease of reducing power with irradiation	Suhaj et al. (2006)
Syzygium aromaticum (L.) Merr. & L.M.Perry	γ-radiation	5, 10, 20 and 30 kGy	Preservation of DPPH scavenging activity, reducing power and total phenols	Suhaj and Horváthová (2007)
Zingiber officinale Roscoe			Preservation of DPPH scavenging activity and reducing power with irradiation; increase of DPPH scavenging activity during storage at 10 and 20 kGy	

Notes: DPPH (2,2-Diphenyl-1-picrylhydrazyl)

Table 14.9 Effects of ionizing radiation on the bioactive content of edible flowers

Edible flower	Radiation source	Doses applied	Main results	References
Viola tricolor L.	γ-radiation	0.5, 0.8 and 1 kGy	Higher amounts of phenolic compounds at 1 kGy; increase of DPPH scavenging activity and β-carotene bleaching inhibition at 1 kGy	Koike et al. (2015a)
	e-beam	0.5, 0.8 and 1 kGy	Higher amounts of phenolic compounds at 1 kGy; highest DPPH scavenging activity and β-carotene bleaching inhibition at 1 kGy	
Tropaeolum majus L.	γ-radiation	0.5, 0.8 and 1 kGy	Increase of non-anthocyanin phenolics and decrease of anthocyanin concentrations with irradiation; decrease of DPPH scavenging activity with irradiation; increase of β-carotene bleaching inhibition at 1 kGy	Koike et al. (2015b)
	e-beam	0.5, 0.8 and 1 kGy	Increase of non-anthocyanin phenolics and decrease of anthocyanin concentrations with irradiation; decrease of DPPH scavenging activity with irradiation; enhancement of β-carotene bleaching inhibition at 1 kGy	

Notes: DPPH (2,2-Diphenyl-1-picrylhydrazyl)

14.6.8 Mushrooms

Mushrooms are one of the most perishable products and their short shelf-life is an obstacle for the distribution of the fresh product (Fernandes et al. 2013a). In fact, some studies highlighted the use of gamma irradiation as a conservation process since the results showed that this technology is effective in maintaining the chemical characteristics of *Lactarius deliciosus* L., *Boletus edulis* Bull.: Fr and *Hydnum repandum* L.: Fr (Fernandes et al. 2013a, b). Several studies were performed in order to evaluate the effect of gamma and electron-beam irradiation in the antioxidant properties of different wild and cultivated mushrooms species. Fernandes et al. (2013c) demonstrated that gamma radiation at 0.6 kGy was the most efficient method to preserve the chemical composition of fresh *Macrolepiota procera* (Scop.) Singer when compared with other processing treatments such as freezing (at −20 °C) and drying (at 30 °C). Fernandes et al. (2014) studied the effects of electron-beam irradiation on different dried wild mushrooms (*B. edulis* Bull. and *Russula delica* Fr.) on nutritional, chemical and antioxidant parameters. The antioxidant activity was improved significantly at 6 kGy for both mushroom species, attributed to the increased levels of tocopherols. The same effect was observed in the antioxidant activity for *Amanita caesarea* and *A. curtipes* irradiated at 2, 6 and 10 kGy, which was correlated with the increase in the levels of phenolic compounds (Fernandes et al. 2015). Studies in fresh samples of *Agaricus bisporus* Portobello using gamma and electron beam radiation were performed to evaluate the effectiveness of these technologies on the conservation of this mushroom (Cardoso et al. 2019). In that work, gamma radiation treatment was associated with the increase of ergosterol, monounsaturated fatty acids and β-tocopherol, while e-beam led to higher values of polyunsaturated fatty acids.

Regarding the irradiation of truffles, total phenolics content significantly increased in *Tuber aestivum* after gamma irradiation with 1.0–2.5 kGy (Adamo et al. 2004; Tejedor-Calvo et al. 2020), although ergosterol and total sterols concentrations did not significantly change (Tejedor-Calvo et al. 2020). However, in irradiated *T. melanosporum* no significant changes were noticed in sterols even after storage of 35 days. Moreover, electron beam irradiation at 2.5 kGy enhanced the concentration of phenolic compounds up to 21 days of storage by almost three-fold (Tejedor-Calvo et al. 2019). Table 14.10 gathers the effects of irradiation treatments on the bioactive compounds of mushrooms.

14.7 Valorization of Food Bioactives: A Forthcoming Application of Food Irradiation

Although bioactive compounds are naturally present in many foods, after suitable isolation and purification, they can be used as ingredients on the development of functional foods, on cosmetics and/or on health care products.

Irradiation treatment can improve the food bioactivity, as it was highlighted in the previous sections. This potentiality could be applied to valorize other products through the improved extraction of bioactive compounds from irradiated materials and further incorporation in food, cosmetic or pharmaceutical products. To the best of our knowledge there is no documented application regarding the use of bioactives from irradiated sources in other products, but there are several encouraging outputs on the incorporation of bioactive compounds in food that will be detailed bellow.

The fortification of food through the incorporation of bioactive compounds in order to improve their quality or biological properties has been explored, especially in yogurts, meat, sausages or bread (Dall'Asta et al. 2013; Amirdivani and Baba 2014; Ribas-Agustí et al. 2014; Guiné et al. 2016; Turgut et al. 2017). Green tea (*Camellia sinensis*) infusions used during milk fermentation to produce yogurt were reported to promote the growth of beneficial yogurt bacteria and enhance the antioxidant activity of yogurt (Amirdivani and Baba 2014). Guiné et al. (2016) obtained yogurts enriched with antioxidants extracted from wine, observing an increase in antioxidant activity without affecting acidity. Chestnut flour was utilized in the formulation of functional bread (Dall'Asta et al. 2013), with a ratio of 50/50 (soft wheat/chestnut flour) leading to the highest value of antioxidant capacity in the final product. Moreover, bread produced with wheat flour fortified at 1, 2, and 3% (w/w) with dried leafy vegetable presented higher concentrations of polyphenols and higher values of antioxidant activity than the controls (Alashi et al. 2019). Other study investigated the incorporation of pomegranate peel extract at 0.5% and 1.0%

Table 14.10 Effects of ionizing radiation on mushrooms bioactive compounds

Mushroom	Radiation source	Applied doses	Main results	References
Lactarius deliciosus L.	γ-radiation	0.5 and 1.0 kGy	Reduction of total tocopherols; increase of phenolics at 0.5 kGy; increase of antioxidant activity at 0.5 kGy	Fernandes et al. (2013a)
Boletus edulis Bull.:Fr.	γ-radiation	1 and 2 kGy	Increase of δ- and γ-tocopherols at 1 kGy; increase of MUFA and decrease of PUFA at 1 kGy; preservation of total phenolics at 2 kGy; increase of TBARS formation inhibition; decrease of DPPH scavenging activity	Fernandes et al. (2013b)
Hydnum repandum L.:Fr.			Increase of δ-tocopherol at 1 kGy; increase of MUFA and decrease of PUFA at 1 kGy; higher total phenolic content at 1 kGy; increase of lipid peroxidation inhibition; decrease of DPPH scavenging activity	
Macrolepiota procera (Scop.) Singer	γ-radiation	0.6 kGy	Increase of MUFA content; enhancement of α- and γ-tocopherol contents; decrease of phenolics; increase of β-carotene bleaching inhibition and TBARS inhibition	Fernandes et al. (2013c)
Boletus edulis Bull.	e-beam	2, 6 and 10 kGy	Higher concentration of *p*-coumaric acid at 2 kGy; higher concentration of cinnamic acid at 10 kGy; increase of total tocopherols with irradiation; decrease of total phenolics with irradiation; higher DPPH scavenging activity and β-carotene bleaching inhibition at 6 kGy	Fernandes et al. (2014)
Russula delica Fr.			Higher concentrations of gallic acid and cinnamic acid at 6 kGy; higher values of total tocopherols and total phenolics at 6 kGy; higher DPPH scavenging activity and β-carotene bleaching inhibition at 6 kGy	
Amanita caesarea (Scop.) Pers.	e-beam	2, 6 and 10 kGy	Increase of *p*-hydroxybenzoic acid concentration at 2 kGy; increase of MUFA at 10 kGy; higher values of tocopherols at 10 kGy; increase of total phenolics with irradiation; increase of antioxidant activity with irradiation	Fernandes et al. (2015)
Amanita curtipes Gilbert			Increase of MUFA at 10 kGy; increase of tocopherols; increase of total phenolics at 10 kGy; increase of antioxidant activity at 10 kGy	
Agaricus bisporus Portobello	γ-radiation	1, 2 and 5 kGy	Higher amount of ergosterol at 2 kGy	Cardoso et al. (2019)

(continued)

Table 14.10 (continued)

Mushroom	Radiation source	Applied doses	Main results	References
	e-beam		Higher amount of ergosterol at 2 kGy	
Tuber aestivum	γ-radiation	1.0, 1.5 and 2.5 kGy	Increase of phenolic compounds at 1.5–2.5 kGy	Adamo et al. (2004)
		0.5, 1.0, 1.5 and 2.5 kGy	Increase of total phenolics with irradiation; preservation of total sterols.	Tejedor-Calvo et al. (2020)
Tuber melanosporum	γ-radiation	1.5 and 2.5 kGy	Decrease of total phenolic compounds at 2.5 kGy; preservation of total sterols	Tejedor-Calvo et al. (2019)
	e-beam		Increase of total phenolic compounds at 1.5 kGy; preservation of total sterols	

Notes: DPPH (2,2-Diphenyl-1-picrylhydrazyl); FRAP (Ferric reducing power); TBARS (Thiobarbituric acid reactive substances); MUFA (Monounsaturated fatty acids); PUFA (Polyunsaturated fatty acids)

concentrations in beef meatballs which was effective on retarding lipid and protein oxidations and on preventing rancid odor formation (Turgut et al. 2017). Moreover, Ribas-Agustí et al. (2014) demonstrated that it is possible to produce dry fermented sausages with natural antioxidants from grape seed and cocoa extracts without changing their sensory properties. Recently, a maceration industrial-scale extraction process was demonstrated to be effective on the recovery of bioactive compounds from unripe red grapes (cv. Sangiovese) with a high extraction yield (Fia et al. 2020). The obtained extract showed greater phenolic compound and water-soluble vitamin contents and antioxidant activity than those measured in the traditional product (called "verjuice") obtained from unripe grapes. The process was suitable to be transferred to the wine industry to produce extracts that can be used as ingredients for other industries and enhance the sustainability of the wine sector.

Concerning the pharmaceutical industry, natural bioactive compounds, in particular, omega-3 fatty acids from fish and fish oil, plant sterol esters and/or phenolic compounds from, e.g., green tea or red wine, have been combined with major hypolipidemic drugs. This co-therapy appeared to be safe and effective to prevent or treat cardiovascular diseases progression (Scolaro et al. 2018) even if further research has to be done to understand the biochemical mechanisms involved in these protective effects.

Relating to the use of food bioactive compounds in cosmetics products, there are some *in vivo* studies in the literature with positive results. In a study with 20 volunteers, it was demonstrated that a formulation containing green tea extract was able to inhibit the photoaging and tumor generation (Li et al. 2009). Also, a product developed as a combination of resveratrol, green tea polyphenols and caffeine was evaluated in a 12-week study with 16 volunteers and revealed to reduce facial redness (Ferzli et al. 2013). Black grape seed extract was also efficiently used in a water-in-oil cream as demonstrated to increase the skin elasticity, decrease erythema effects and/or skin sebum content (Sharif et al. 2015). Nevertheless, it becomes important to continue studying the best way to recover bioactive compounds from food products and also to explain their potential added-value to the producers.

There are some patents on the application of bioactive compounds extracted from food sources in pharmaceutical and functional foods. As an example, a method to produce grape extracts with high values of Oxygen Radical Absorbance Capacity (ORAC) was patented to be added to foodstuffs and nutritional supplements as a beneficial antioxidant (Ying et al. 2011). The development of nutraceutical products from the antioxidants present in different fruits extracts and, in particular, from *Grewia asiatica* L. (phalsa) was patented based on their *in vitro* and *in vivo* antioxidant potential (Choudhary et al. 2014). Furthermore, a nutraceutical composition using resveratrol in combination with other components, e.g. genistein, lycopene, hydroxytyrosol or polyunsaturated fatty acids, was patented for delaying aging and/or for the treatment or prevention of age-related diseases in animals was patented (Raederstorff et al. 2008). Also, the production of pharmaceutical formulations to deliver biologically active compounds in a controlled manner so as to increase the bioavailability of compounds protecting them from *in vivo* degradation, has been the object of patents (Yuhua and Chien 2009). Slavko (2012) also invented a new pharmaceutical formulation that comprises silica earth, resveratrol, grape seeds extract, green tea extract and tomato powder with antioxidant effects.

14.8 Concluding Remarks

Food products are extremely rich in bioactive compounds. Due to the growing demand in society for new ingredients that can be reused on foods, cosmetics or pharmaceuticals, scientific communities are searching and developing new formulations and optimizing extraction processes. The findings presented in this chapter turn evident the potential added-value of the bioactive compounds extracted from irradiated plant and food sources. Nevertheless, further research should be performed on their applicability for the preparation of new formulations in different industries.

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